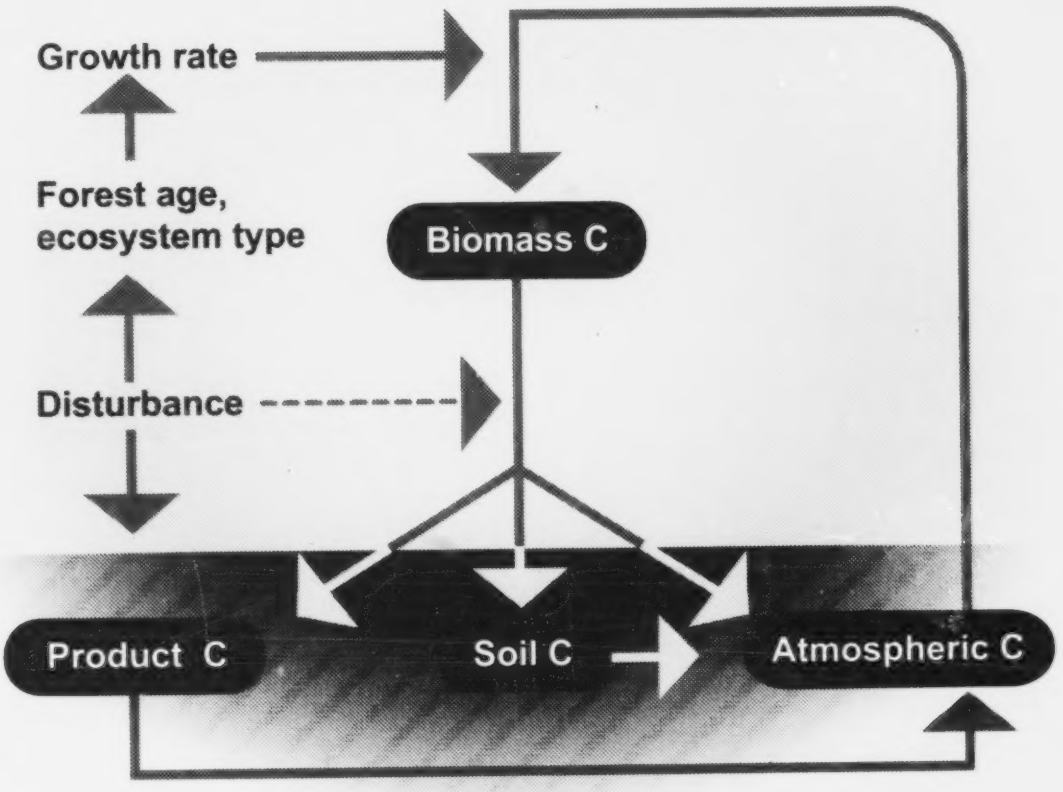
Forest Research Report No. 158

Ontario

Quantifying Ontario's Forest Carbon Budget

1. Carbon Stocks and Fluxes of Forest Ecosystems in 1990



Ministry of Natural Resources

Ontario Forest Research Institute
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Quantifying Ontario's Forest Carbon Budget

1.Carbon Stocks and Fluxes of Forest Ecosystems in 1990

by

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Executive Summary

Under the Kyoto Protocol, Canada has agreed to reduce its greenhouse gas (GHG) emissions by 6% from 1990 levels by 2010. Canada's current forest and forest carbon budget measurement systems will not likely satisfy the measurement requirements of the Kyoto Protocol. Ontario must clearly define its needs, investigate detailed carbon (C) budgets, and report on its C sinks and sources. In response, the Ontario Ministry of Natural Resources (OMNR) has developed a strategic approach to the design and implementation of climate change programs in support of Ontario's commitment (OMNR 1999). One of the first critical steps is to quantify the 1990 C stocks and fluxes on managed forest lands in Ontario.

In this study, we adapted the well-established *Carbon Budget Model for the Canadian Forest Sector* (CBM-CFS2) (Apps and Kurz 1991; Kurz et al. 1992; Kurz and Apps 1999), which is a national-scale model of forest sector C budgets, to estimate the C stocks and fluxes of Ontario's forest ecosystems. We used extensive provincial and national databases, including forest inventory and growth and yield plot data and ecosystem disturbance records.

Preliminary results suggest that about 12.65 Pg C (10^{15} g C) (including 1.70 Pg C in biomass and 10.95 Pg C in forest floor and soil) was stored in Ontario's forest ecosystems in 1990, which amounts to about 15% of the national forest C budget. Geographically, forest age structure, C stocks, and C density are significantly different among the 3 ecoclimatic regions across the province. Average C density was 179 Mg ha^{-1}, including 24 Mg ha^{-1} for biomass and 155 Mg ha^{-1} for litter and soil. About 87.7% of total C is estimated to reside in the boreal region of northern Ontario, while only 12.3% occurs in the temperate region of southcentral Ontario. For all of Ontario's forest ecosystems about 0.27 Pg C was absorbed by forests in 1989-1990. Annual litterfall is estimated at 0.23 Pg C, of which 0.11 Pg is from aboveground and 0.12 Pg is from belowground biomass. Annual C release to the atmosphere from forest litter and soil is estimated at 0.30 Pg C. Although the moderate temperate zone of southern Ontario was estimated to be a small C sink of 0.68 Tg C, the net C balance of Ontario's forest ecosystems was estimated at about -0.03 Pg C for 1990, indicating forests act as a small net CO_2 source and provide positive feedback to global warming. However, this study does not include C taken up and released by forested peatlands or the forest products sector. These are currently being investigated.

Keywords: climate change, Kyoto Protocol, greenhouse gases, carbon budget model, carbon balance

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Introduction

Climate change is widely considered to be one of the largest threats to the sustainability of the Earth's environment, and the well-being of its people. Most scientists agree that the Earth's climate is changing from the build-up of greenhouse gases (GHG), principally carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), that result from anthropogenic activities such as electricity generation, transportation, and agriculture (Houghton et al. 1990). CO_2 is the primary GHG and has been increasing steadily since 1958 (Keeling et al. 1989). Predictions of future climate change caused by increasing atmospheric CO_2 and its potential effects on human environment and health have led to international concerns about the production of GHG (Houghton et al. 1995).

The global carbon cycle is the most important process linking forests to climate change. Forests play an important role in the global C cycle because they store a large amount of C in vegetation and soil, exchange C with the atmosphere through photosynthesis and respiration, are atmospheric C sinks during regrowth after disturbance, and become a C source when they are disturbed by human or natural causes (e.g., forest fires, insect outbreaks, harvesting) (Dixon et al. 1994, Steffan et al. 1998). Through forest management, people can change forest ecosystem C pools and fluxes, and thus affect atmospheric CO_2 concentrations (Apps and Price 1996). Forests cover about 45% of Canada, which has about 10% of the world's forested area. Hence, the C budget of Canada's forests significantly contributes to global C cycles (Kurz et al. 1992, Kurz and Apps 1999).

The international response to climate change includes the United Nations Framework Convention on Climate Change (UNFCCC). Agreed to in 1992, the Convention is a framework for action to limit or reduce GHG emissions. In 1997, 159 countries signed the Kyoto Protocol to the Convention, committing industrialized countries to reducing their GHG emissions. Under the Kyoto Protocol, Canada has agreed to reduce its GHG emissions by 6% from 1990 levels by 2010. However, Canada's total emissions increased between 10 and 13% from 1990 to 1996. To meet the commitment, Canada will have to reduce GHG emissions by 21 to 25% over the next 12 years (IISD 1998). Canada's current forest and forest C budget measurement systems are not likely to satisfy the reporting requirements from the Kyoto Protocol. Canada is faced with 3 requirements: (1) providing an annual inventory of GHG emissions and removals; (2) quantifying 1990 C stocks on managed forest land; and (3) documenting changes in C stocks associated with reforestation, afforestation, and deforestation activities since 1990.

Sixty nine million ha, or 65%, of Ontario's total land area is forested (R. Miller, OMNR, pers. comm.). Ontario needs to investigate detailed C budgets, and report on its C sinks and sources to help in meeting national commitments. In response, the Ontario Ministry of Natural Resources (OMNR) has developed a strategic approach to the design and implementation of climate change programs in support of Ontario's role in the national commitment (Colombo et al. 1998, OMNR 1999). One of the first critical steps is to quantify the 1990 C stocks on managed forest lands, and to assess changes in C stocks associated with reforestation, afforestation, and deforestation activities since 1990.

This report describes the use of a well-established *Carbon Budget Model for the Canadian Forest Sector* (CBM-CFS2) (Apps and Kurz 1991, Kurz et al. 1992, Kurz and Apps 1999) to investigate the C budget of Ontario's forest ecosystems. The objectives of this study are to 1) estimate C stocks and fluxes in Ontario's forest ecosystems; 2) evaluate their contribution to the forest C budget of Canada for the base year 1990; and 3) identify the uncertainties, gaps, and future challenges in fully quantifying Ontario's forest C budget over time.

Methods

Model Description

The CBM-CFS2 model (Apps and Kurz 1991, Kurz et al. 1992, Kurz and Apps 1999) is a general framework for dynamically accounting for C stocks and fluxes in forest ecosystems. It incorporates data and simulated processes required to estimate the C budget of the forest, including C storage in above- and belowground biomass and soils, and C exchange among these reservoirs and the atmosphere (Figure 1). It simulates forest growth, mortality, decomposition, and the effects of disturbances on the forest ecosystem. The effects of disturbance (principally wildfires, insect attacks, and harvesting) on forest age structure and C releases to the atmosphere and forest floor are calculated on a 5-year cycle. Details about the model's structure are available in Kurz et al. (1992), Kurz and Apps (1999), and Apps et al. (1999). The model generates detailed output files and summary information for each spatial unit and ecoclimatic province in Canada. It can provide estimates of the C stocks and fluxes for Ontario's forested land.

The CBM-CFS2 model has been used at national (Kurz and Apps 1995, 1999), provincial (Kurz et al. 1996b), and forest management unit scales (Price et al. 1996; 1997). For example, it has been used to:

(1) demonstrate the importance of natural disturbances as a major factor governing large-scale temporal dynamics of C in Canadian forests over the last century (Kurz and Apps 1995, 1996), possible outcomes in the future (Kurz and Apps 1995), and the role of forest products in this balance (Apps et al. 1999);

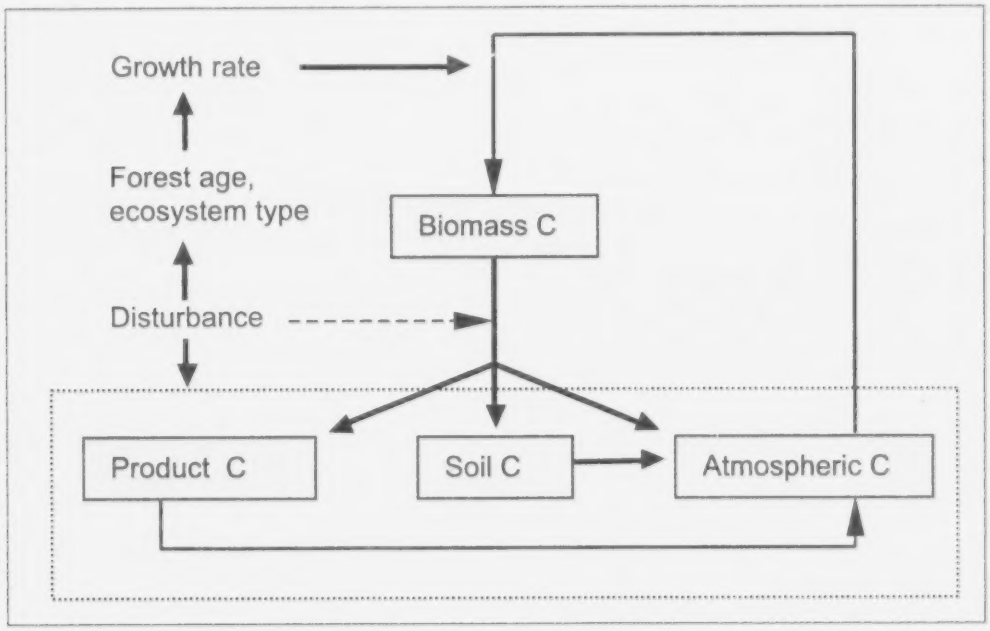


Figure 1: A simple diagram representing carbon stocks and fluxes used in the Canadian Forest Sector Carbon Budget Model (CBM-CFS2).

(2) assess the effects of intensive harvesting on C dynamics (the Foothills Forest in Alberta) compared with those likely to have occurred in the same ecosystem subject only to natural disturbances (Price et al. 1997);

(3) assess the effects of the transition from a natural to a managed disturbance regime in different forest biomes in Canada (Kurz et al. 1998); and

(4) examine various policy implications, including the role of Canada's forests in meeting the Kyoto Protocol, and the sensitivity of national GHG accounting under IPCC (Intergovernmental Panel on Climate Change) guidelines to different data and assumptions (Greenough et al. 1997).

Inventory Data and Spatial Units

This section documents data and assumptions used in the CBM-CFS2 model that are specifically relevant to Ontario. Forest inventory information used by the CBM-CFS2 model is derived from the National Forest Biomass Inventory (NFBI) (Bonnor 1985). The NFBI contains about 50,000 grid cells for all of Canada's forested land and includes considerably more area (440.8 M ha) than the forest inventory since it estimates biomass in low productivity areas and non-commercial forests. Information in the NFBI was summarized for 42 spatial units representing the boundaries of ecoclimatic provinces (Ecoregions Working Group 1989). For the CBM-CFS2 model, Ontario's forested land is divided into 4 ecoclimatic regions (Figure 2): subarctic (SA), boreal (BO), cool temperate (CT), and moderate temperate (MT). The subarctic region has no forest cover or biomass. The other regions contain 45 forest ecosystem types that have been classified using the following criteria: land type class, productivity, stocking, forest type, and site quality. Within each ecoclimatic region, spatial boundaries are not defined for these forest ecosystem types but their area is known. Forest ecosystem types are further split by age classes for C budget accounting. Each record in the database represents a specific age class of a specific ecosystem type within an ecoclimatic region, but the exact location is not known.

Growth Curves

In the CBM-CFS2 model, forest growth is described by a growth curve (i.e., biomass over age) that identifies 4 phases of stand development: regeneration, immature, mature, and overmature (Kurz and Apps 1999). Each phase is represented by a specific growth curve that indicates the annual net accumulation of aboveground biomass. A pair of tree growth curves (one for each of hardwood and softwood species) describes each ecosystem type. Currently, the model uses 45 forest types with 90 growth curves to present aboveground biomass dynamics of forest ecosystems in Ontario. For each growth curve, the parameters for each growth phase, and the rules for transitions between growth phases, are derived from the NFBI. Growth rates are derived from forest growth curves based on age. Light, leaf area, tree species, and soil water content variables are not included.

Forest biomass is divided into 6 parts for each softwood and hardwood component in the CBM-CFS2 model, including: foliage (A), branch and top (B), sub-merchantable (C), merchantable (D), fine roots (E), and coarse roots (F) (Figure 3). Belowground biomass, that is coarse and fine roots, are estimated for softwood and hardwood species using regression equations developed by Kurz et al. (1996a).

Figure 7

Disturbances

Soil Carbon Dynamics

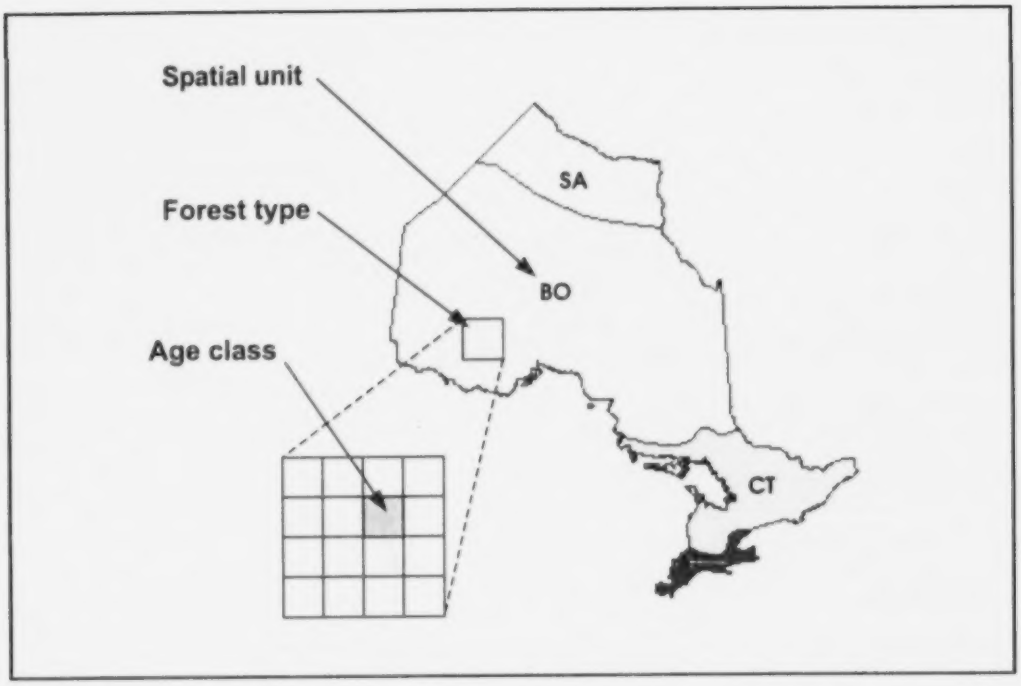


Figure 2: Three spatial data levels of the CBM-CFS2 model, where SA refers to subartic, BO to boreal, CT to cool temperate, and MT to moderate temperate.

Disturbances

Disturbances play an important role in the development of Ontario's forest stands because they are often stand-replacing and thus change overall forest age structure. The CBM-CFS2 model identifies 7 types of disturbances: forest fire, insect-induced stand mortality, clearcut logging, clearcut logging with slash burning, salvage logging following fire, salvage logging following insect-induced stand mortality, and partial cutting. For each spatial unit and disturbance type, a specific disturbance matrix has been assigned to calculate the proportion of each ecosystem C pool transferred to the atmosphere, forest product sector, or other pools (Kurz et al. 1992). The area affected by each disturbance and the year of disturbance is input to the model. There is no feedback scheme that links forest biomass or age class with the extent and type of disturbance each year. The model uses a set of predefined criteria to allocate disturbance area to ecosystem types and ages. After disturbance, the unaffected area keeps the same properties as before. The disturbed area switches to a new age class (usually the beginning of regeneration). New records are formed in a new time step. If records are combined, the area-weighted C content of each pool is calculated.

Soil Carbon Dynamics

The CBM-CFS2 model distinguishes 4 types of soil C pools: very fast, fast, medium, and slow. These soil C pools receive input from processes such as litterfall, turnover, tree mortality, and disturbances. The very fast pool receives all foliage (A) and fine root biomass (E). The fast pool

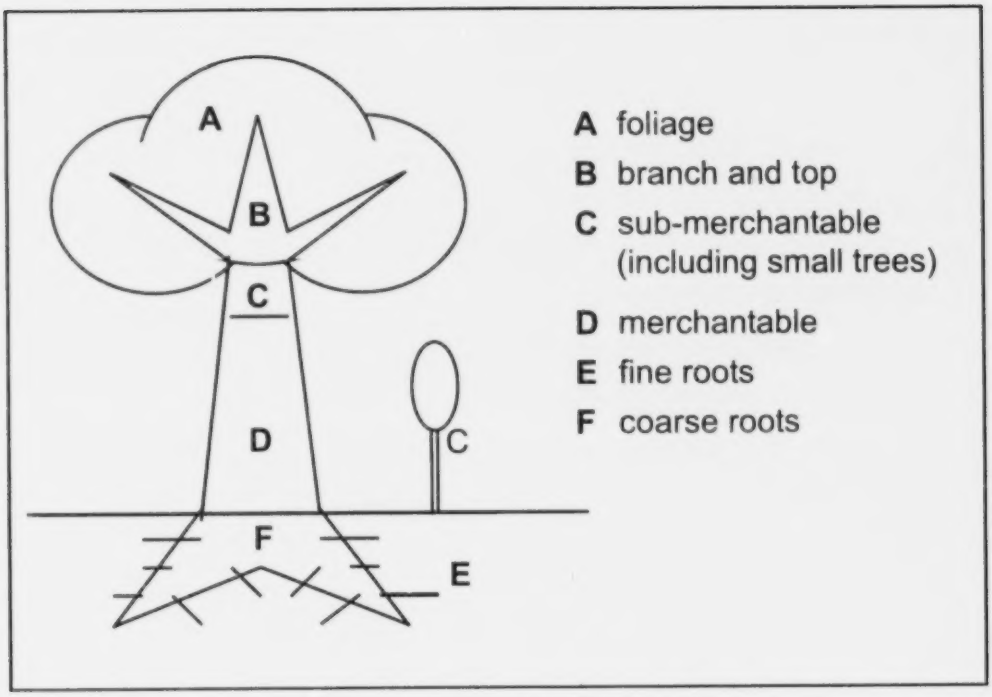


Figure 3: Biomass components of a typical tree in CBM-CFS2 model.

receives tree branch and top biomass (B), sub-merchantable biomass (C) and coarse roots (F). The medium pool receives all stemwood biomass of merchantable trees (D). The slow pool represents humified organic matter and receives its input by decomposition from the 3 pools (Figure 4). Each pool has a different decomposition rate calculated from a base decomposition rate defined at 10°C and adjusted for the mean annual temperature of each spatial unit, assuming a Q_{10} of 2 (i.e., for every 10°C increase in temperature, decomposition rates double) (Kurz and Apps 1999). Since CBM-CFS2 does not simulate the dynamics of forest peat C, estimation of peat C pools and fluxes is not included in this report.

CBM-CFS2 Input Data and Runs

The CBM-CFS2 simulation was retrospective to the 1920s, so we can not only evaluate current C condition, but also can look at the trends over the past 70 years. Input data were mainly based on the forest biomass inventory database of 1985 (see Kurz and Apps 1992, 1995, 1999). For the entire Ontario region, there are 45 forest types available. Each forest type contains 2 growth curves (hardwood and softwood), resulting in a total of 90 growth curves for Ontario's forest ecosystems. Growth curves were parameterized based on inventory data. Decomposition rates and disturbance matrixes were derived from various data sources and published literature (Kurz et al. 1992, Kurz and Apps 1999). In this study, model simulations began in 1989 with simulated initial ecosystem conditions that are the endpoint of the 70-year retrospective model run for the period

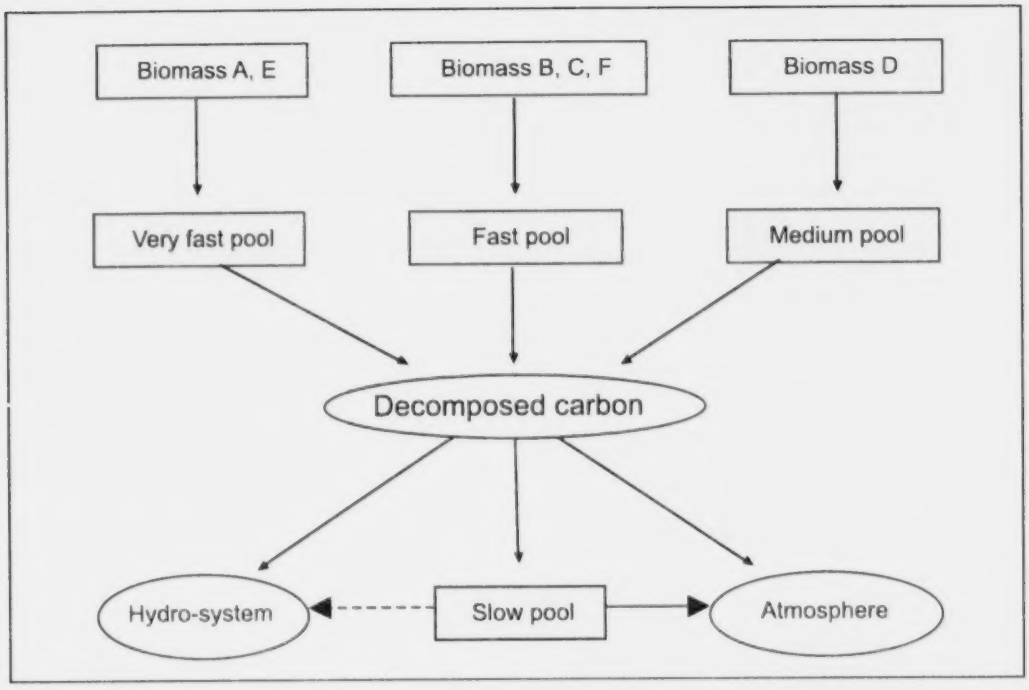


Figure 4: Schematic of soil carbon fluxes. A refers to foliage, B to branch and top, C to sub-merchantable tree, D to merchantable tree, E to fine roots, and F to coarse roots, as per Figure 3.

1920-1989 (Kurz et al. 1995, Kurz and Apps 1999). The distribution of forest age classes and the biomass C and soil C pools are all affected by the forest dynamics of the 70-year period prior to 1990. Further details on the assumptions underlying the retrospective analysis can be found in Kurz et al. (1995) and Kurz and Apps (1999).

Results

Forest Age Structure

Age structure is a key component of forest landscapes, and largely determines the distribution of C stocks in different forest ecosystems. Age structure is strongly affected by ecosystem disturbances (such as forest fire, insects, and harvesting). In Ontario, boreal and cool temperate regions have similar age-class structures (Figure 5) with a large proportion of young forest because of frequent forest fires between 1985 and 1989 (Perera et al. 1998). In contrast, older forests (over 80 years) are more prominent in the moderate temperate region. Less frequent disturbances, less human intervention, and different forest types, all of which affect C dynamics, account for these differences.

Ecosystem Carbon Stocks

Table 1 provides general information about estimated forest carbon distribution in Ontario's forest ecosystems. Detailed descriptions are provided below.

Biomass C stocks and their distribution across 3 ecoclimatic regions in 1990 are shown in Figure 6.

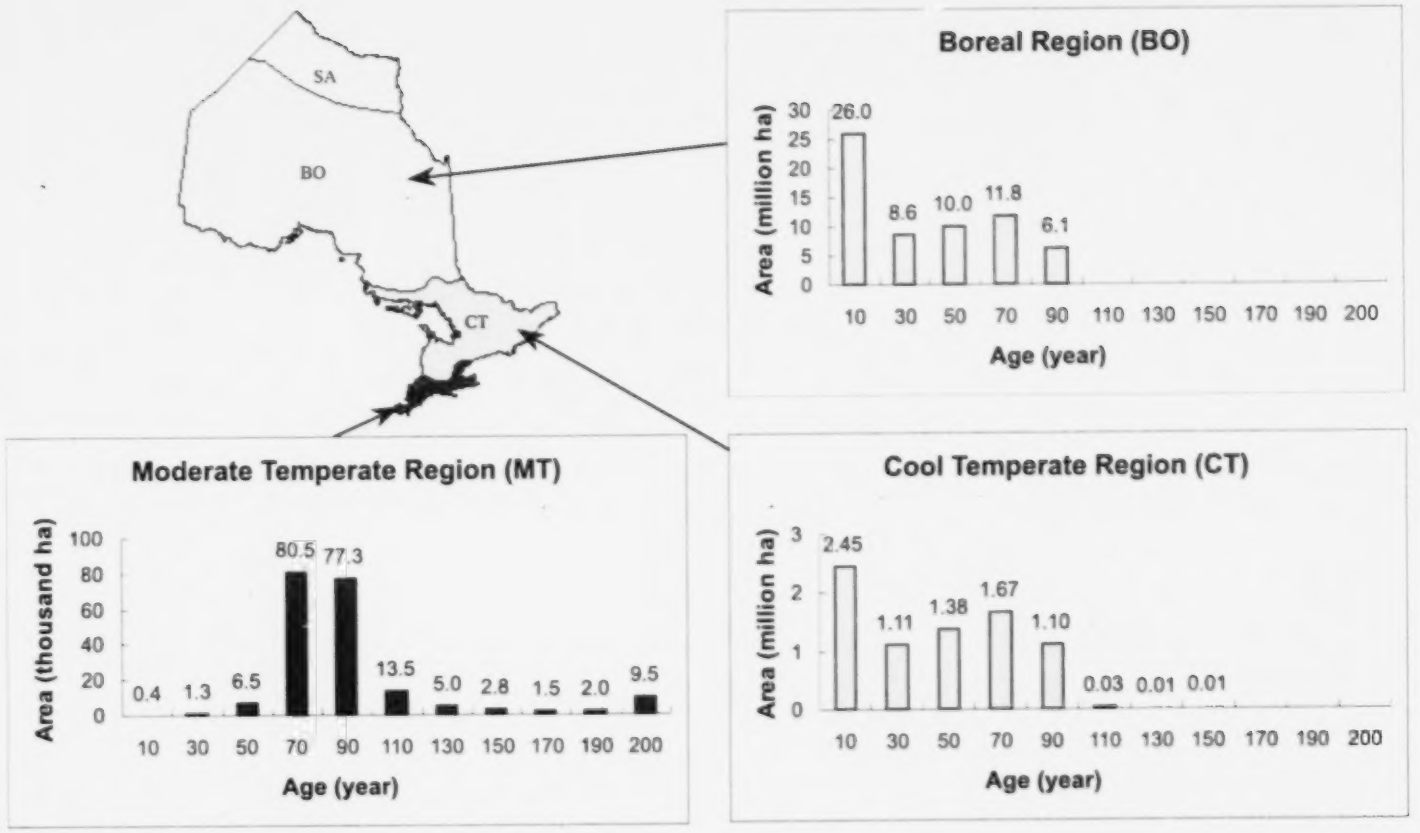


Figure 5: Ontario's forest age class structure in 1990.

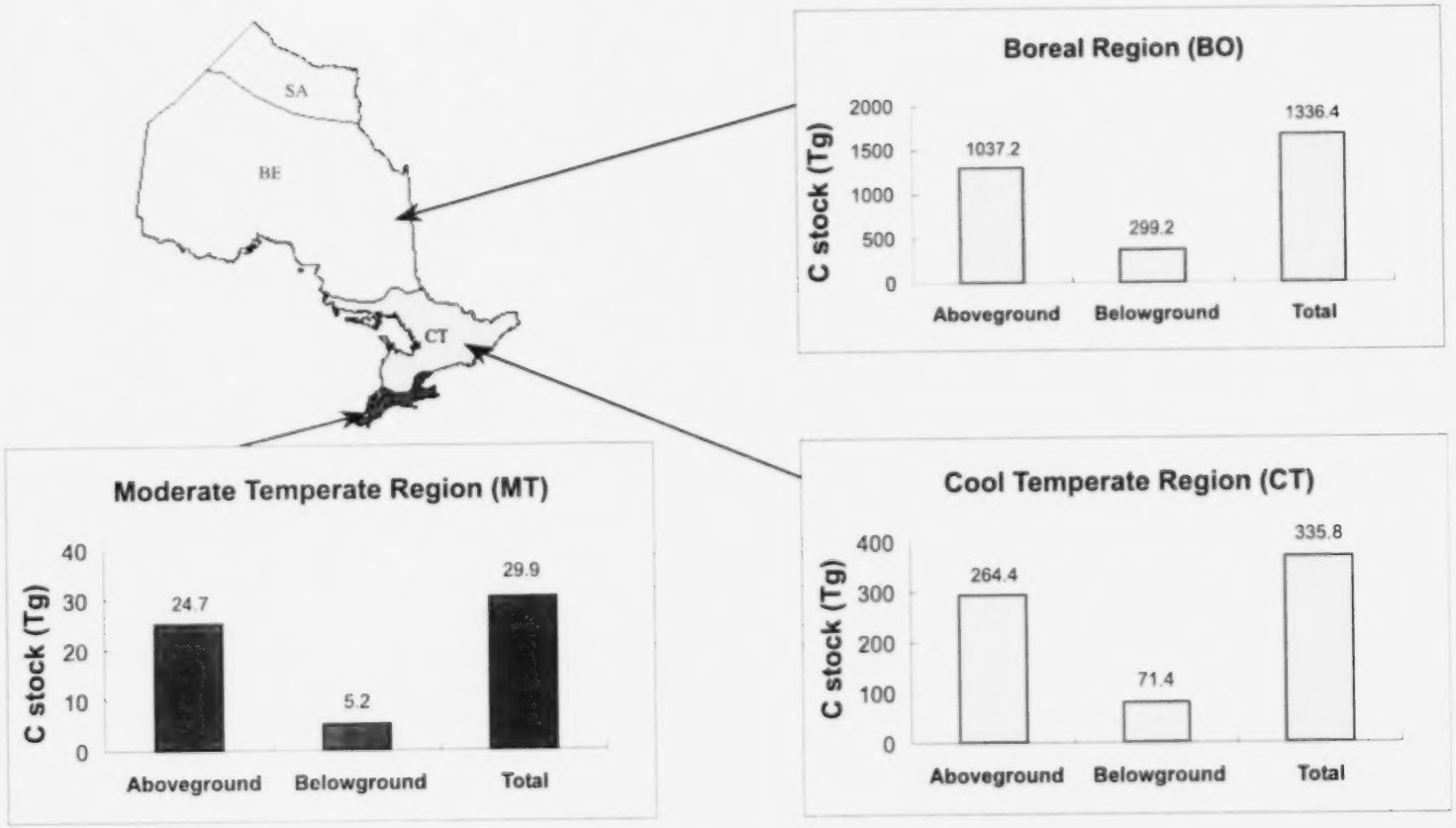


Figure 6: The estimated distribution of biomass carbon stocks in Ontario's forest ecosystems in 1990.

Above- and belowground biomass are distributed as expected within the ecosystem except that in the moderate temperate region, total biomass was unexpectedly low. Biomass C stocks are 12.1% of total ecosystem C stocks for boreal, 22.8% for cool temperate, and 44.4% for moderate temperate regions, showing an increasing gradient of forest biomass C from north to south.

The structure of soil C stocks are similar in the 3 regions (Figure 7). Slow soil pools in each region account for 71-78% of total soil C content, yet the remaining soil C pools, comprised of the fast, very fast, and medium subsoil pools, are estimated to produce 90% of total soil C emissions to the atmosphere. Percentages of fast plus very fast soil C stocks in these regions are 16.3% for boreal, 17.3% for cool temperate, and 20.5% for moderate temperate, respectively.

Ecosystem Carbon Fluxes

Annual ecosystem C flux is presented in Figure 8a. In 1990, total C sequestering through tree growth was estimated at about 268 Tg C yr^{-1} (1 Tg = 10^{12} g) and about 299 Tg C yr^{-1} was released to the atmosphere by litter and soils decomposition. The net C balance of the ecosystem was estimated to be about -32 Tg yr^{-1}, which indicates a net C source to the atmosphere for the base year of 1990 due to disturbance related release. The geographical distribution of C balance was varied. For example, the boreal zone (Figure 8b) was estimated to be a small source with 31.5 Tg C yr^{-1}, followed by cool temperature zone (Figure 8c), with 1.1 Tg C yr^{-1}. The moderate temperate zone (Figure 8d) was estimated to be a small C sink with 0.68 Tg C yr^{-1} for the base year of 1990. However, this study doesn't include absorption by peatland or the release of C from forest products and harvesting which may affect the C source-sink relationship.

As expected, C uptake by the boreal region is calculated at about 222 Tg C yr^{-1}; i.e., 83% of total ecosystem C uptake, mainly due to its large area (89% of total ecosystem area). About 16% of C uptake occurs in the cool temperate region, and only 1% of uptake occurs in the moderate temperate region. C released by boreal, cool temperature and moderate temperate were calculated to be about 85%, 14% and 1% of total ecosystem C emissions, respectively.

Table 1. General properties of Ontario's forest ecosystems. BO= boreal region, CT=cool temperate region, and MT= moderate temperate region. Forest land area is estimated from 1985 National Forest Biomass Inventory (Bonnor 1985).

Region	Forest ecosystem types	Average forest age (years)	Forest land area (M ha)	Biomass C stock (Tg C)	Litter and soil C stock (Tg C)	Biomass C density (Mg C ha^{-1})	Litter and soil C density (Mg C ha^{-1})
BO	15	43	61.22	1336	9761	21	156
CT	16	47	7.77	336	1148	43	148
MT	14	94	0.20	30	37	149	187
Overall	45	44	69.19	1702	10946	24	155

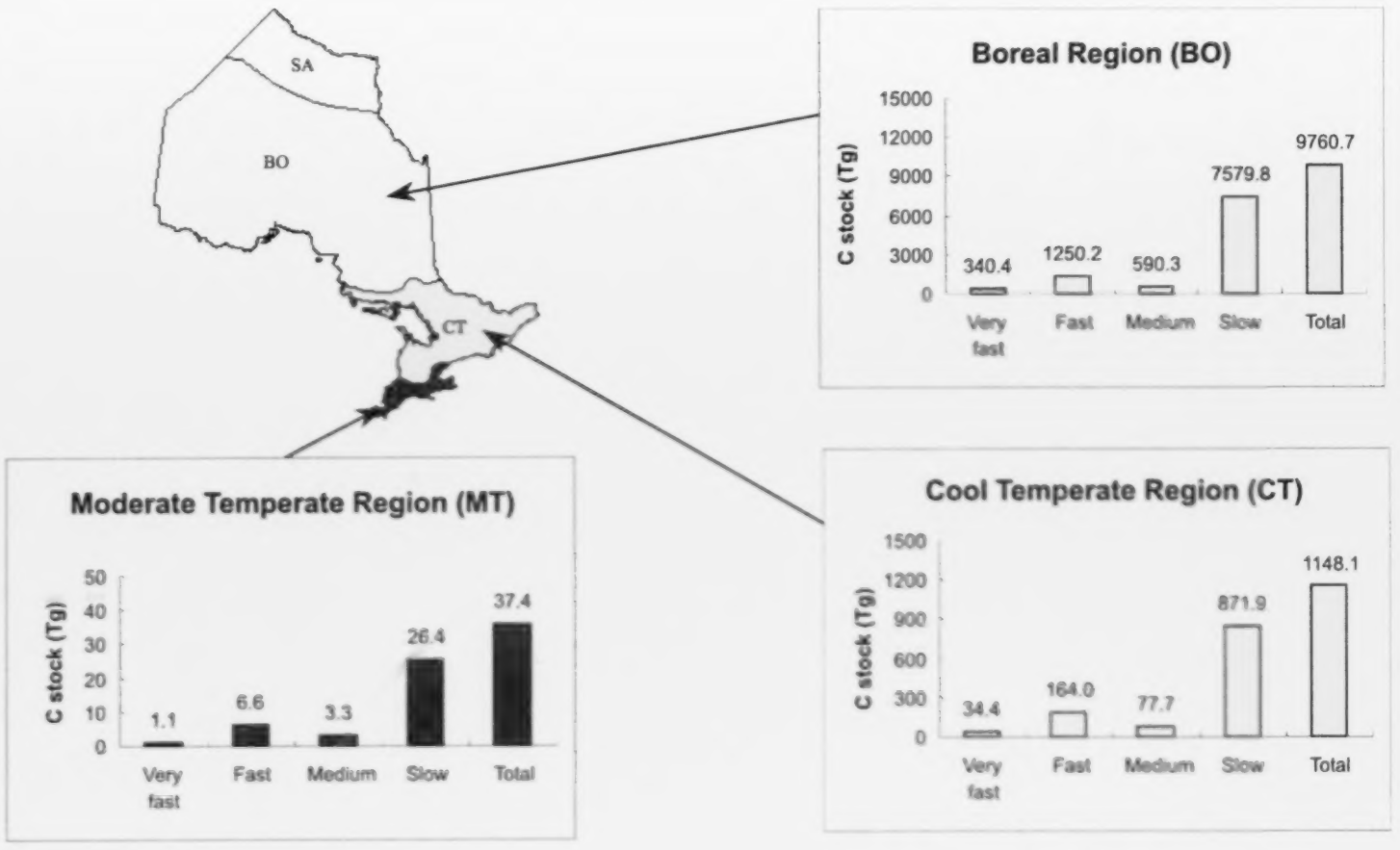
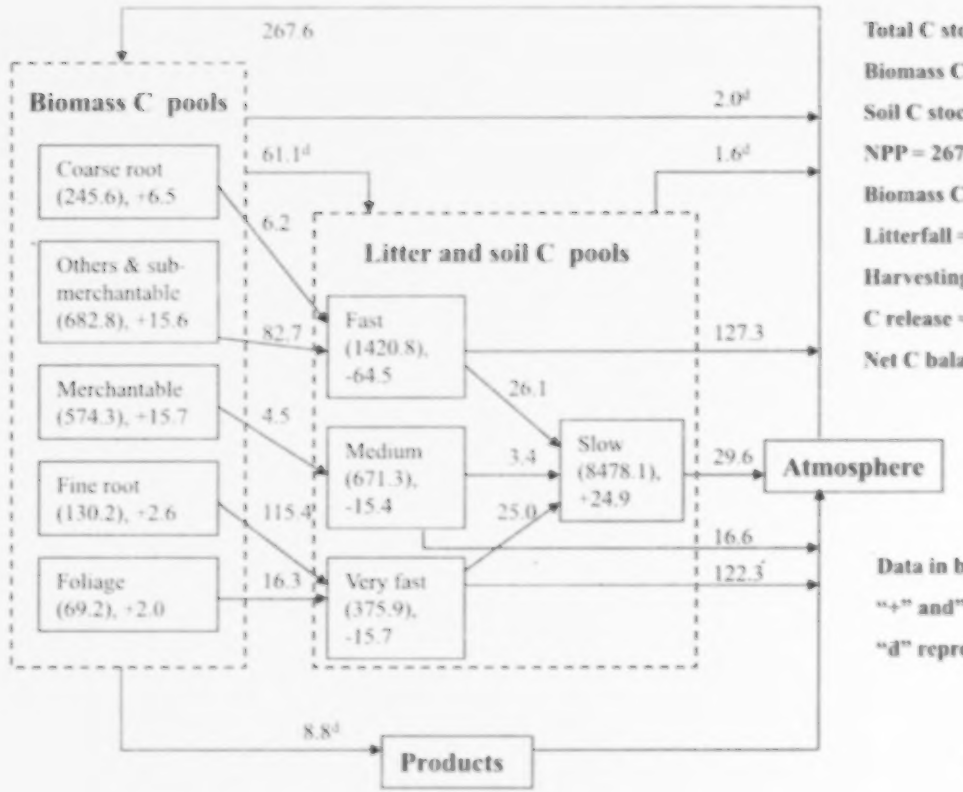


Figure 7: Estimated litter and soil carbon stocks of Ontario's forest ecosystems in 1990.



Total C stock = 12648.2 Tg =12.65 Pg

Biomass C stock =1702.0 Tg =1.70 Pg

Soil C stock = 10946.2 Tg = 10.95 Pg

NPP = 267.6 Tg yr^{-1} (Total C absorbed by forests)

Biomass C increment = 42.5 Tg yr^{-1} (Before disturbance)

Litterfall = 225.1 Tg yr^{-1} (Before disturbance)

Harvesting = 8.8 Tg yr^{-1} (C goes to forest production)

C release = 299.4 Tg yr^{-1} (C released to atmosphere)

Net C balance = -31.8 Tg yr^{-1} =-0.03 Pg yr^{-1}

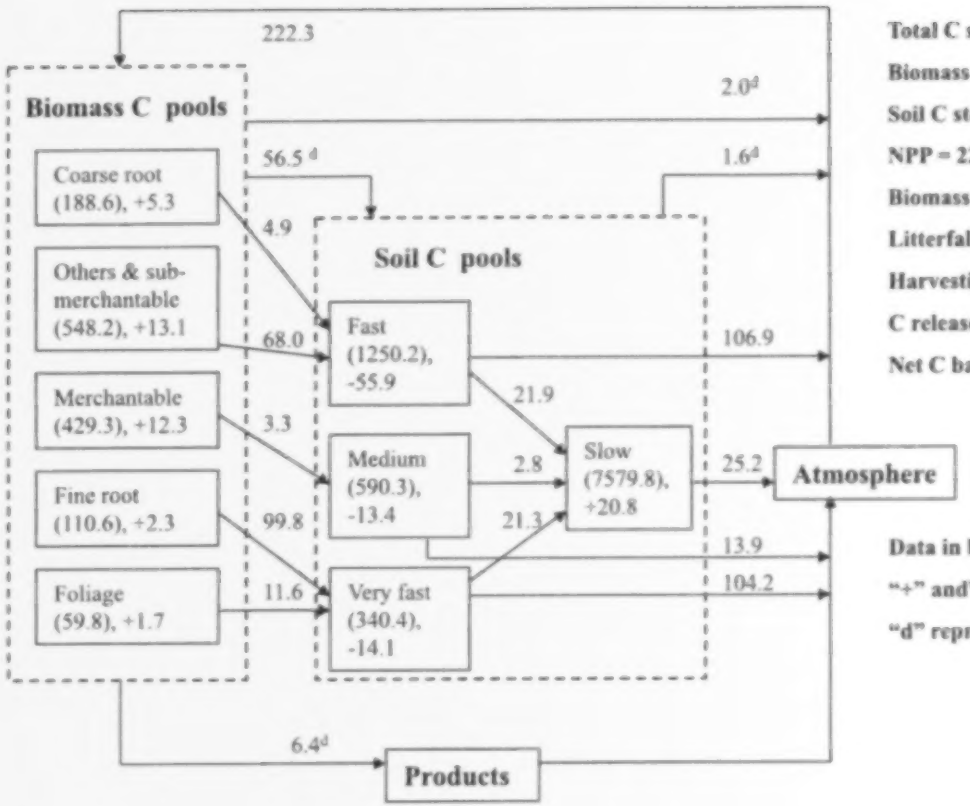
Data in brackets show C stock at the end of simulation,

"+" and" -" indicate net C change before disturbance,

"d" represents C flow caused by disturbance

(1 Pg C = 10^3 Tg C= 10^{15} g C)

Figure 8a: Carbon fluxes (Tg yr^{-1}) of Ontario's forest ecosystems (1989 - 1990).



Total C stock = 11097.1 Tg

Biomass C stock =1336.4 Tg

Soil C stock = 9760.7 Tg

NPP = 222.3 Tg yr^{-1} (Total C absorbed by forests)

Biomass C increment = 34.7 Tg yr^{-1} (Before disturbance)

Litterfall = 187.6 Tg yr^{-1} (Before disturbance)

Harvesting = 6.4 Tg yr^{-1} (C goes to forest production)

C release = 253.8 Tg yr^{-1} (C released to atmosphere)

Net C balance = -31.5 Tg yr^{-1} = -0.03 Pg

Data in brackets show C stock at the end of simulation,

"+" and" -" indicate net C change before disturbance,

"d" represents C flow under disturbance

(1 Tg C = 10^{12} g C)

Figure 8b: Carbon fluxes (Tg yr^{-1}) of Ontario's boreal region (BO) (1989 - 1990).

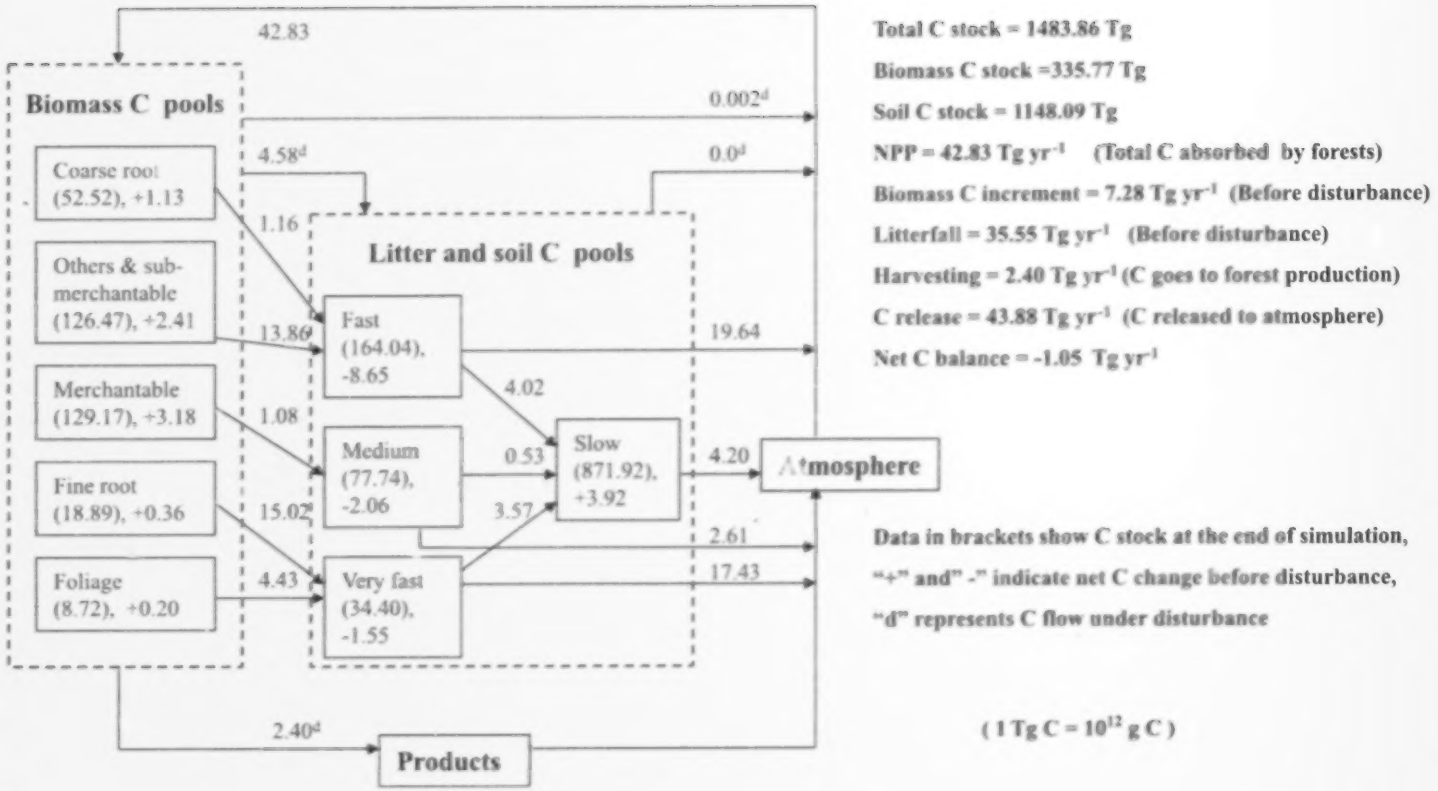


Figure 8c: Carbon fluxes (Tg yr^{-1}) of Ontario's cool temperate region (CT) (1989 - 1990).

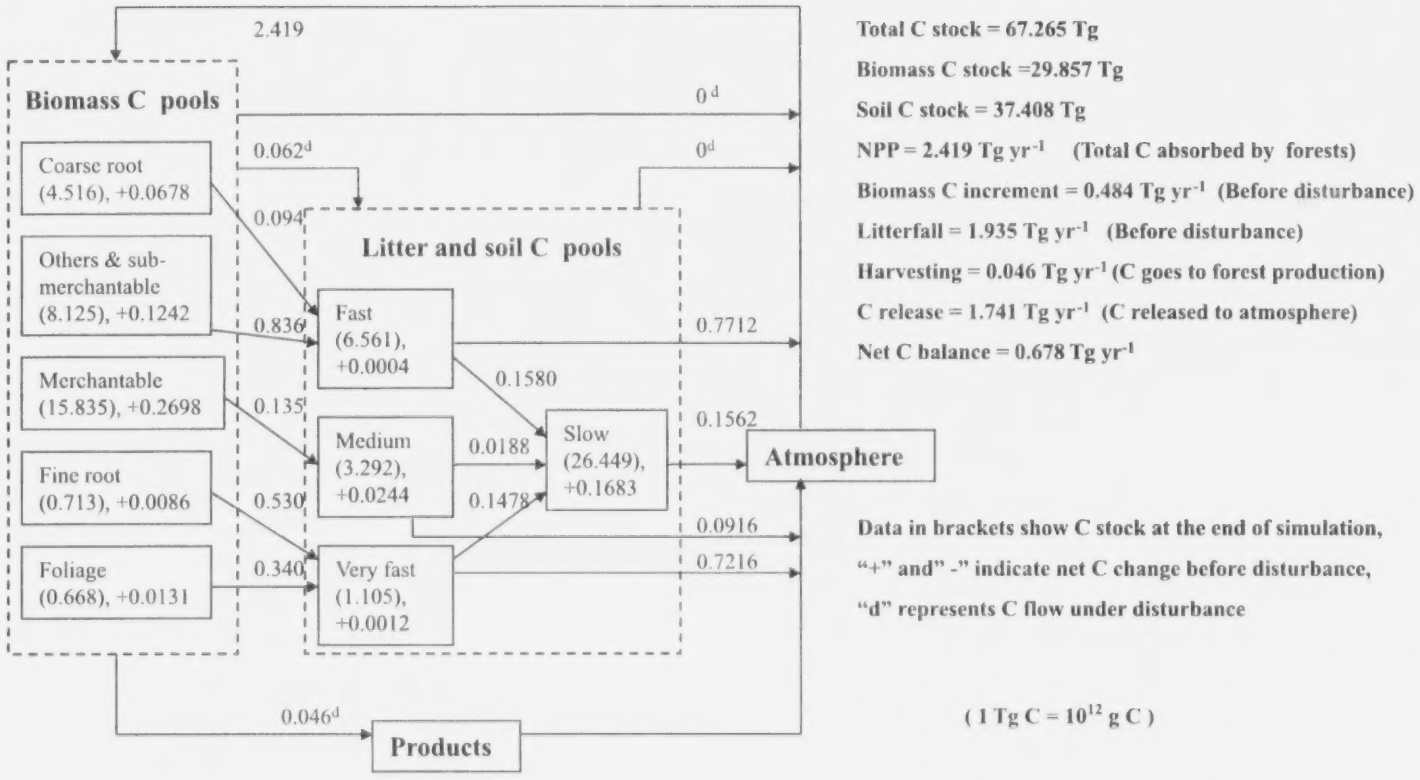


Figure 8c: Carbon fluxes (Tg yr^{-1}) of Ontario's moderate temperate region (MT) (1989-1990).

Discussion

Contribution of Ontario's Forest Ecosystems to Canada's Carbon Budgets

With about 38% of Canada's population and 17% of Canada's forest land, Ontario plays a significant role in Canada's economy. What is the contribution of Ontario's forest to the Canadian C budget? Figure 9 shows that Ontario's forest ecosystems contributed about 15% of the national C budget for the base year 1990 (Kurz and Apps 1999), including 12% of C in living biomass and 16% of C in litter and soil. However, it is important to realize that Ontario has the highest CO_2 emissions (i.e., 166 Tg C) among the provinces in Canada for 1990 (IISD 1998). To meet the Kyoto targets, the Government of Ontario, like the Government of Canada, is committed to a series of action plans to stabilize Ontario's GHG emissions, to maintain and enhance existing C sinks, and to reduce potential C sources. Recently, OMNR has developed a strategic approach to the design and implementation of climate change programs in support of Ontario's commitment under the Kyoto Protocol (Colombo et al. 1998, OMNR 1999).

The results reported in this study focus on Ontario's forest ecosystems, and do not include C storage and fluxes in the forest products sector. Although C storage in Canadian forest products contain less than 1% of total forest sector C, they increased by nearly 25 Tg C yr^{-1} in 1989 (Apps et al. 1999).

Forest Management Mitigation Options

The total amount of C stored in forest ecosystems simply equals the forested area multiplied by C density (storage per ha). Sequestration strategies should logically focus both on increasing the storage per ha and on increasing the total forested area (Winjum et al. 1993, Binkley et al. 1997). There has been growing interest in the use of intensive forest management as a means of increasing forest productivity and wood production to offset loss of forests to non-forestry uses (Bell et al. 2000). Intensive forest management is now being considered as an alternative approach to promote forest C sequestration and to offset C emissions (Binkely et al. 1997, Colombo et al. 1998, Papadopol 2000, Parker et al. 2000). The inclusion of other potential forest management practices that may sustain and increase the capacity for C sequestration (e.g., tree improvement; fertilization; changes in rotation length; stocking control and thinning; appropriate harvest method; protecting against fire; insect and disease; and maintaining forested areas) could be strategic mitigation options for Ontario when negotiating provincial C accounting under the Kyoto Protocol (Parker et al. 2000). However, the Kyoto Protocol currently identifies only reforestation, afforestation, and deforestation in accounting for CO_2 to meet emission reduction targets.

Current Gaps and Future Challenges

Although the major components of biotic C budgets in Ontario are CO_2 uptake by terrestrial ecosystems and release by decomposition and disturbance (such as fire, insects, and harvesting), other processes are ongoing that may affect net C balance. For example, C uptake and emission by forest products and forested peatland. These processes are potentially important, but detailed data and simulation models for Ontario are currently unavailable or limited.

The C budget of the Canadian forest products sector plays an important role in the net forest

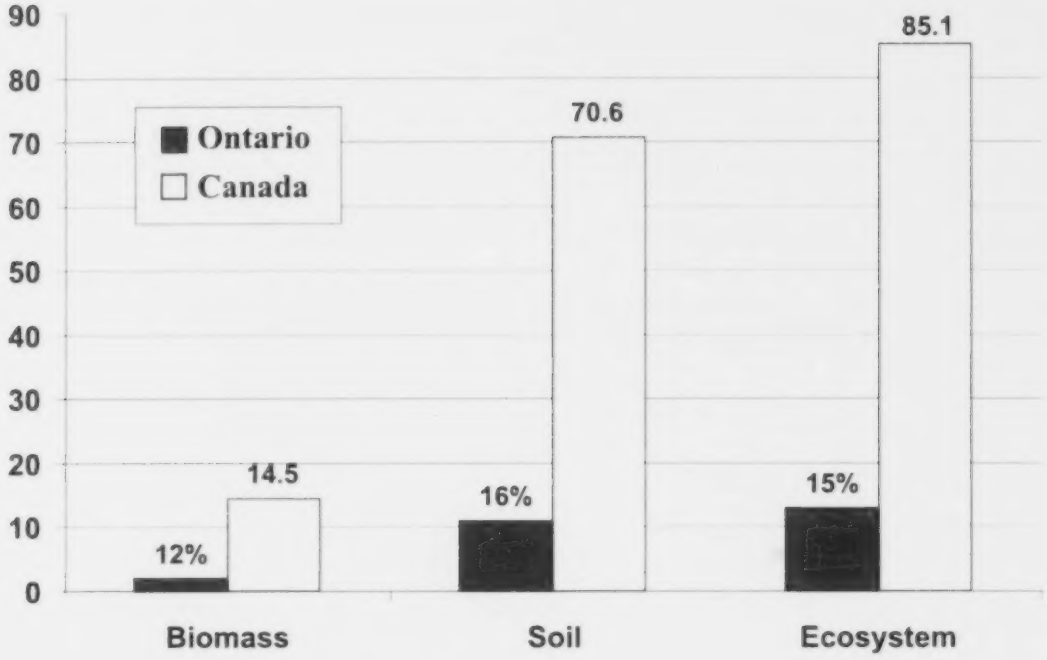


Figure 9: Estimated contribution of Ontario's forest ecosystems to Canada's forest carbon budget in 1990. Ontario's contribution relative to national carbon stocks is 15%.

sector exchange with the atmosphere and offsets more than 30% of the net C released from Canadian forest ecosystems reported by Kurz and Apps (1999) for that period. Not all C removed from forest ecosystems went to the atmosphere; a portion of the C removed from the ecosystem has been retained in the forest product sector resulting in a lower net release to the atmosphere. Unfortunately, the Ontario C budget of the forest products sector has not been explicitly provided by Apps et al. (1999), and is not known because the movement of forest products across provincial boundaries is not recorded. Further investigation of detailed C stocks and emissions by Ontario's forest product sector since 1990 is required before a full C budget can be provided for Ontario's forest ecosystems.

There have been significant recent advances in our understanding of peatland C dynamics, but these are still primarily qualitative, mainly due to a weakness in the mechanistic understanding of the peatland C processes and their interaction with other pertinent ecosystems (i.e. forests) (Gorham 1991, Frolking et al. 1998, Moore et al. 1998, Yu and Campbell 1998, Zoltai et al. 1998). Well established forest peatland C dynamic models are not available for Canada, although progress has been made in developing peatland C dynamic simulation models by some groups in Canadian research institutes and universities (Apps et al. 1994, Honeywill and Roulet 1997, Halsey et al. 1998, Yu and Campbell 1998, Hilbert et al. 2000). Further detailed investigation of C stocks and fluxes in these additional C pools presents a continuing challenge.

Recommendations

Improve Spatial Resolution and Incorporate New Local and Provincial Databases

To increase the accuracy of the Ontario simulation, the spatial resolution of CBM-CFS2 should be increased. In current estimations only 3 spatial units are broadly considered for Ontario's forest ecosystems. The model should now be run using Hill's 12 site regions (Hills 1959). Further work is also required to calibrate model input data using local PSP (permanent sample plot) data sets held by Ontario's forest growth and yield program as well as other existing databases.

Develop Dynamic Forest Growth Modules by Incorporating Ecophysiological, Climatic, and Environmental Factors

The CBM-CFS2 model includes only limited process-level simulation of the response of forest ecosystems to changes in the global environment (Price and Apps 1993; Kurz and Apps 1999). The forest growth curves used to represent biomass dynamics were adequate in that they recognized 4 phases of stand development (Kurz and Apps 1994, 1999). However, the parameters for each growth phase, and the rules for the transitions between growth phases, are directly derived from inventory data such as NFBI, and growth rate is a dependent variable of forest age. Variables such as climate, light, leaf area, tree species, and soil water content are not considered in the growth curves. Although the effects of changes in environmental conditions during past periods on forest growth dynamics may already be accounted for in the inventory data, and may be partially represented in the growth curves used by the CBM-CFS2 model, changes over time will not be captured in the current formulation. For this reason, the current formulation of CBM-CFS2 does not explicitly predict the effects of changes in temperature, precipitation, atmospheric CO_2 concentration or N deposition, on the process of growth and decomposition (Price and Apps 1993, 1999, Peng and Apps 1998, Kurz and Apps 1999). One of challenges for future work with the CBM-CFS2 model will be the representation of ecosystem processes by incorporating dynamic forest growth modules in a version modified for Ontario.

Conduct Further Sensitivity Analyses

To meet the coming Kyoto commitment associated with the Canadian 2008-2012 Kyoto Protocol target, changes in future C stocks and fluxes must be predicted for Ontario's forest ecosystems. This will require using models such as CBM-CFS2 in a predictive capacity. To increase our understanding of these predictions, some sensitivity analyses are required. These include:

- Running the model at different spatial scales (ecoclimatic regions and Hill's site regions) to determine the differences between high resolution and low resolution runs;
- Testing the effects of changes associated with reforestation, afforestation, and deforestation on forest ecosystem C pools and net balance;
- Testing the importance of changing the model's disturbance matrix for specific fire disturbance (crown vs. surface) and forest management regimes, such as changes in land-use that would be associated with intensive forest management; and
- Determining the effects of changes in the forest product sector including increases in the use of biomass energy, recycled paper and wood, and net changes in C emissions associated with product substitution.

Conclusions

This report presents a preliminary estimation of C pools and fluxes for Ontario's forest ecosystems using the well-established dynamic C accounting model, CBM-CFS2, for the base year 1990. Results suggest that about 12.65 Pg C (including 1.70 Pg in biomass and 10.95 Pg in forest floor coarse woody debris and soil) were stored in Ontario's forest ecosystems in 1990, which amounts to about 15% of Canada's 1990 forest C stocks. The annual net C balance of Ontario's forest ecosystems was estimated to be about -0.03 Pg for 1990. Thus forest ecosystem C decreased slightly; some of this C was stored in forest products, the remainder released to the atmosphere.

There is potential to increase C sinks and to reduce C sources through appropriate forest management practices in Ontario. Intensive forest management practices that may enhance forest C sequestration and offset C emissions (e.g., tree improvement; fertilization; changes in rotation length; stocking control and thinning; appropriate harvest methods; and fire, insect, and disease protection measures) are now being considered as strategic mitigation options (Colombo et al. 1998; Parker et al. 2000). This study does not include C taken up and released by forested peatland or the forest products sector. To fully quantify the C budget of Ontario's forest ecosystems, further investigation of these important components is required.

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